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Performance and degradation analysis for long term reliability of solar photovoltaic systems: A review

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ABSTRACT

Electricity generated using photovoltaic (PV) technology can only be economical if the PV modules operate reliably for 25–30 years under field conditions. In order to ensure such levels of reliability PV module undergo stringent qualification tests developed as per international standards by International Electro-technical Commission. These tests provide excellent information regarding module design, material and process flaws which can lead to premature failure. Even the well qualified modules are found to fail or degrade more than their expected levels when exposed to the outdoor conditions, indicating that these tests are not adequately addressing the real outdoor conditions and are not sufficient to estimate the module lifetime. Keeping in view this aspect, the performance and degradation analysis studies of solar photovoltaic modules, accelerated aging testing under laboratory and outdoor field testing conditions, are reviewed. The factors affecting the performance of PV module, PV module degradation modes, stress factors responsible for degradation, accelerated aging tests and current PV module qualification standard tests are also discussed along with recently used techniques for the failure mode analysis of PV modules. The main objective of the study is to review the literature on performance and degradation of PV modules under outdoor operation for identifying research gaps for long term reliability of PV modules and improving the PV qualification standards for various geographical and climatic conditions.

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1. Introduction

The global energy needs have increased significantly in the past several decades and are predicted to rise more than 50% by 2030 [1]. This enhancement in the energy consumption in developing countries is due to the rapid industrialization and development. At present the energy needs are met mostly from the conventional sources of energy like coal, gas and oil, which are exploited in an unsustainable manner resulting in exhausting the global reserves of fossil fuels in the near future. The large scale consumption of fossil fuels, is also damaging the environment. Thus, there is a need to shift from conventional to renewable sources of energy which are both sustainable and environment friendly. However, at present renewable energy sources share a very small portion of the energy market worldwide. The solar energy resource is renewable, abundant and freely available across the globe. The photovoltaic (PV) system which convert sunlight to electricity, is a promising renewable energy alternative from future prospects.

Electricity generation using PV technology is increasing rapidly throughout the world during the past decade. The PV systems have become reliable and are considered one of the potential alternatives for power supply needs both in remote regions and urban areas. PV module cost accounts for 70 to 80% of total PV systems cost. With the advancement in PV technology the cost of PV module has declined steadily, from 3.50 $/Wp for first generation solar cells to 1.0 $/Wp for second generation solar cells. This cost is further expected to decrease to 0.50 $/Wp [2]. The Government policies for providing financial incentives, such as feed in tariff for solar-generated electricity, have further supported the growth of solar PV installations in many countries. For example there is a steady increase in total installed PV system capacity from 103 MW in 1992 to 63611 MW in 2011 in countries participating in the IEA-PVPS programme [3].

The price of PV generated electricity depends upon the price of PV module and its lifetime. The cost economics related with the PV systems can only be effective if PV systems operate reliably for more than 20 years. To ensure such levels of reliability, PV modules undergo rigorous qualification tests as per International Electro-technical Commission (IEC) standards [4,5]. These tests are commonly referred to as design qualification and type of approval tests. The severity and duration of these tests are so designed to assess the PV modules reliability and quality. These tests help in minimizing the infant mortality of PV modules. However, these tests are not useful in estimating the module lifetime. The performance of PV modules under actual outdoor conditions is found to be quite different than that determined under controlled laboratory conditions during qualification or certification testing. This difference is due to the fact that under actual outdoor conditions, solar radiation, temperature, humidity, wind and operating voltage are experienced together, whereas during certification or qualification testing such conditions are applied as per specific predetermined sequence. The generation of variety of defects and their growth during outdoor operation degrade the performance of PV modules, leading to premature failure. Recent studies on degradation/failure modes of PV modules and to improve quality standards have shown that even the qualified modules sometimes have failed or degrade more than the predicted levels [6,7]. Therefore, it is necessary to study the behavior of PV modules under actual outdoor conditions to understand their performance, degradation, losses in energy yield, nucleation, growth and impact of defects. These studies help in quantifying long-term behavior and estimate module lifetime time.

The main objective of the paper is to review the literature on performance and degradation of PV modules under outdoor operation for identifying research gaps for long term reliability of PV modules and improving the PV qualification standards for various geographical and climatic conditions.

The paper is organized as follows: In Section 2, an overview of the PV technology is given, in Section 3, PV system performance evaluation methodology and review of studies on performance evaluation of PV systems at different locations are presented. A review of PV module degradation studies under field conditions and controlled lab conditions is described in Section 4. The various techniques developed to understand and analyse the degradation mechanism of PV modules, are summarized in Section 5. The conclusion of the study is given in Section 6.

2. Overview of PV technology

2.1. PV module

Solar cells can be electrically connected in series and/or parallel to provide desired voltage and current outputs. Thus the solar cells are sorted in to different groups after fabrication as per their efficiency and peak power. Solar cells with efficiency and peak power as close as possible are then joined together electrically to form a PV module. This is done to minimize the mismatch losses in a module. In order to ensure long life of solar cells, they are required to be protected from the various environmental conditions such as thermal cycling, dust, rain etc. when they operate outdoors. Thus to protect solar cells and ensure a long operating period, PV module include following components:

- Transparent front glass
- Encapsulated solar cells string

- EVA layers
- Back sheets

Solar cells are protected by sandwiching them between the encapsulant. Most often used material as encapsulant is EVA (ethylene-vinyl-acetate). In order to provide the mechanical strength to flat-plate photovoltaic module, low iron, toughened and textured glass about 3.2 mm thickness is used in the front side. This cover glass has high transmitivity (90% for most of the solar spectrum) and serves several purposes in module like mechanical rigidity, impact resistance, electrical isolation of solar cell circuit and outdoor weather variability. The backsheet of the PV module is usually non transparent, with a multilayer structure consisted of polyester film (PET), laminated between polyvinyl fluoride (PVF) commonly known as tedlar (TPT) or tedlar, PET, EVA (TPE). Module with transparent back side is also possible. Such modules are often used in buildings integrated (BIPV) applications. Front glass, encapsulant, electrically connected cells and PVF are arranged together and placed in the laminator. Inside the laminator the air is removed through the vacuum pump and pressure is applied from the top of the chamber to remove remaining air and moisture inside the laminate. During this process module is kept at temperature 80 to 100 °C such that EVA melts and act as an adhesive by forming bonds between front glass and back tadler sheet after cooling. Laminated module is heated to 150 to 200 °C temperature this process is known as curing. At this high temperature polymerization of EVA takes place and result into formation of cross link of chemical bonds, thus providing durability and strength to EVA sheet for long term operation. The quality and lifetime of the PV module depends upon the magnitude and duration of the parameters, like pressure, temperature during construction. Finally module is sealed into aluminum frame and characterized for current voltage (*I*–*V*) and output power rating.

2.1.1. PV module I–V characteristics

Fig. 1 shows the single diode model of a solar cell, and the internal series and parallel resistances. Both light *I*–*V* and dark *I*–*V* measurements are commonly used to analyze the electrical performance of solar cells. These measurements provide most effective way to determine fundamental performance parameters.

The dark *I*–*V* characteristics of a solar cell, is given by

$$I_D = I_0[\exp(qV/kT) - 1], \tag{1}$$

where I_D is dark current I_0: reverse saturation current, q: is the charge on the electron, k: is the Boltzmann constant, T: is the temperature.

The equation describing the light *I*–*V* characteristics of a solar cell is given by

$$I = I_{PH} - I_0[\exp(qV/akT) - 1] \tag{2}$$

where I_{PH}: light generated current, a: diode factor.

The Eq. (2) is the elementary equation of a photovoltaic cell and does not represent the *I*–*V* characteristic of a photovoltaic module. The PV module generally consists of 28–36 connected solar cells and the characteristics of the PV module requires the inclusion of additional parameters in the basic Eq. (2) [8]. The modified single

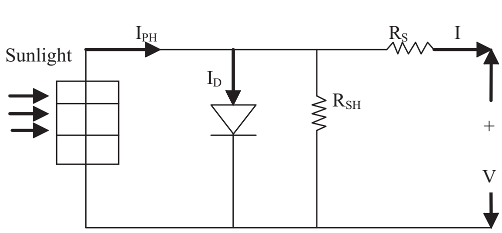

Fig. 1. Single diode model of a PV cell.

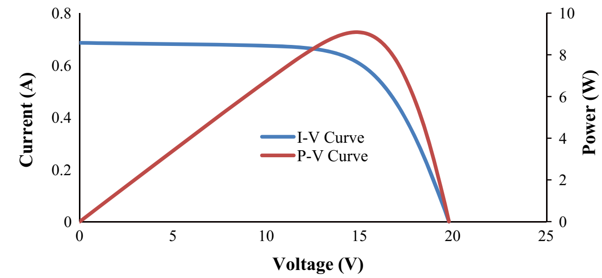

Fig. 2. *I*–*V* characteristic and power curve of a PV module.

diode equation representing PV module is given by

$$I = I_{PH} - I_D - \frac{V + IR_S}{R_{SH}} \tag{3}$$

$$I = I_{PH} - I_0\left[\exp\left(\frac{q(V + IR_S)}{kT}\right) - 1\right] - \frac{V + IR_S}{R_{SH}} \tag{4}$$

The fundamental parameters determined by these equations are short circuit current (I_{SC}), open circuit voltage (V_{OC}), maximum power (P_{max}), fill factor and efficiency. *I*–*V* characteristic along with the power curve of a PV module is as shown in Fig. 2.

2.1.2. PV module rating

The solar PV modules are marketed with their rated peak power (Wp). It is the most important parameter from installer as well as user point of view. Rating of PV module is provided under standard test conditions (STC). STC condition is referred as irradiance of 1000 W/m^2 at air mass 1.5 g and cell or module temperature 25 °C. Such measurement is carried under sun-simulator and process is known as characterization of PV module. General information provided by manufacturer through characterization include following parameters:

V_{oc}	Open circuit voltage
I_{sc}	Short circuit current
V_{max}	Maximum power voltage
I_{max}	Maximum power current
P_{max}	Maximum power rating

However, the conditions specified in STC occur rarely in the real environment because solar irradiance is normally less than 1000 W/m^2 and module temperature is more than ambient temperature or 25 °C. Thus, the output of the PV module is lower than the rated value in the real outdoor conditions. In order to provide more comprehensive picture of output power of PV module, performance of module is tested under other two test conditions: standard operating condition (SOC) and nominal operating condition (NOC). Both of these measurements use different concept of nominal operating cell temperature (NOCT) defined as the cell temperature of open circuited rack mounted module under following conditions:

Irradiation	800 W/m^2
Ambient temperature	20 °C
Wind speed	1 m/s

The NOCT usually lie between 42 and 50 °C. The three test conditions discussed above are summarized in Table 1,

Table 1
Test conditions under which PV modules are characterized.

Conditions	Standard test conditions (STC)	Standard operating conditions (SOC)	Nominal operating conditions (NOC)
Irradiation (W/m^2)	1000	1000	800
Temperature (°C)	25	NOCT	NOCT
Wind speed (m/s)	–	1	1

2.2. Factors affecting the performance of PV module

The performance of a PV module under actual outdoor conditions depends on several factors like type of PV technology used and the environmental conditions of the site where the module is deployed.

2.2.1. Type of PV technologies

A number of PV technologies available are mono-crystalline silicon, poly crystalline silicon, amorphous silicon and other thin film technologies like CdTe, CIS etc. Out of these, crystalline silicon PV technology is well established and shares about 85% of the world′s PV installations. However, upcoming PV cell technologies like triple junction under concentrated sun, are expected to take up the larger share of the PV market in near future [9]. The main advantage of using mono-crystalline silicon cells is high efficiency which ranges between 15 and 18% at present, C–Si solar cell have achieved record efficiency of 25% [10], but the complicated manufacturing processes of these cells result in higher costs. Poly-crystalline cells are simple to manufacture, less expensive but with lower efficiencies ranging between 8 and 12% [11]. Amorphous silicon is the most popular thin film technology with efficiency ranges from 5 to 7% [12]. The CdTe, CIS efficiencies ranging between 16 and 20% [13,14] and triple junction under concentrated sun with highest efficiency values up to 37.4% are also in the development stage [15]. Extensive research is going on to improve the efficiency of PV cells for the commercial use. The efficiency of the PV cell is one of the key parameters on which the performance of a PV module and system depends, which in turn is influenced by temperature, solar irradiance, dust etc.

2.2.2. Effect of ambient temperature

The output power of a PV module depends on the temperature at which the solar cells operate. It is important to note that module temperature is always higher than the ambient temperature. The higher temperature of the module is due to the use of glass cover which traps the infrared radiation. The increase in temperature result in the reduction of band gap of the PV cells in the module [8]. This leads to the increase in I_{SC} but decrease in V_{OC}. The decrease in V_{OC} is more prominent than increase in the I_{SC}.

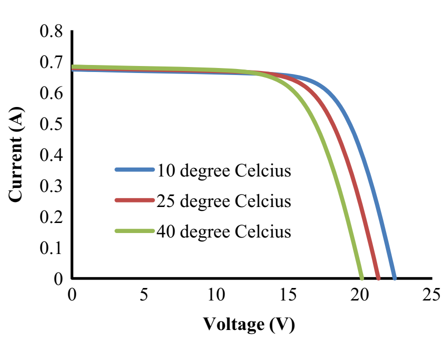

Fig. 3. Effect of temperature on the *I–V* curve of the PV module.

Therefore, overall power output and efficiency of the PV cells decreases with the increase in its operating temperature. The effect of temperature on the *I–V* curve of the PV module is shown in Fig. 3. The efficiency of mono-crystalline PV cell is more influenced by temperature as compared to poly-crystalline and amorphous silicon cells. With the rise in temperature efficiency of mono-crystalline PV cell is found to decrease by 15% whereas amorphous PV cell by 5% [16].

As the temperature increases, power output and efficiency of PV module decreases and becomes minimum at the stagnation temperature [17]. Higher module temperatures also results in degradation of cell-wires, encapsulant as well as influences the module life time in the field.

2.2.3. Effect of solar irradiation

The output power of the PV module strongly depends upon the solar irradiation falling on it. The power output of a module increases linearly with the increase in the incident solar radiation. With the increase in the incident solar radiation more number of photons will be available to move the electrons from balance band to conduction band resulting into production of more current. The effect of solar irradiance on the *I–V* curve of the PV module is shown in Fig. 4.

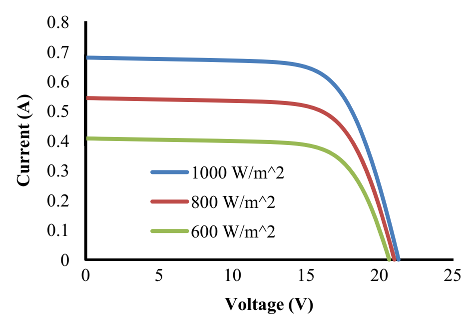

Fig. 4. Effect of solar irradiance on the *I–V* curve of the PV module.

Eikelboom and Jansen [18] studied the effect of irradiance and outdoor exposure on the performance of nine different types of PV technology modules from different manufacturers. After the exposure to outdoor conditions, the CIS and amorphous silicon modules showed strong degradation of the maximum power at STC, whereas mono-crystalline modules did not show any degradation. Finally, it is concluded that thin film PV modules perform better under low irradiance conditions. Yoo [19] investigated the relation between power output and irradiance through outdoor measurements and simulation of a Building Integrated PV in Korea and observed that the output power of PV modules increases with increase in irradiation level. The simulation results also showed good agreement with the experimental result. However, continuous solar exposure for long term also results in the degradation, affecting the performance of PV modules.

2.2.4. Effect of tilt angle of PV module

The performance of PV module depends on amount of solar radiation received by a PV module which in turn depends on the orientation and tilt angle [20,21]. The orientation of modules is generally south in northern hemisphere and north in southern hemisphere. The tilt angle is site dependent and has to be optimized to maximize the incident solar radiation on the surface of PV module. Yadav and Chandel [22] have reviewed various computational methods to determine tilt angle of PV module using different optimization techniques. Thus, in order to increase the energy output of a solar system, PV module should be inclined at optimum orientation and tilt angle determined for the site.

2.2.5. Other factors

In addition there are several factors like dust accumulation, humidity and air velocity which affect the performance of the PV module. A detailed review on the effect of these parameters on the performance of PV module is presented by Mekhilefa et al. [23].

It is clear that the factors discussed above have significant influence on the performance and reliability of the PV systems. The continuous performance evaluation of PV systems, helps in improving the ability of system integrators to design systems with high performance and reliability at lower costs.

3. PV system performance evaluation

An accurate evaluation of photovoltaic (PV) system performance is important for the development of PV industry. The performance evaluation helps the component manufacturers to ensure the quality of their products and to identify future industry needs. There is a need for standard parameters on the basis of which the performance of a PV system can be evaluated. Thus, in order to evaluate the performance of a PV system, the International Electro-technical commission (IEC) has developed standard performance parameters for photovoltaic system performance monitoring and analysis as per IEC standard 61724 [24]. These performance parameters are developed on the basis of following considerations:

- As the output of PV systems differ due to size, geographic location, season, design and technology so, it is difficult to compare various PV systems as such, the developed performance parameters should be able to provide a single base for comparing such PV systems.
- The parameters should be capable of detecting the operational problems and various losses in the PV system.
- The parameters should be able to validate models developed for system performance estimation during the design phase.

3.1. Performance evaluation methodology

The main parameters for evaluation of PV system performance as per IEC standards are as follows:

- Final yield (Y_F)
- Reference yield (Y_R)
- Performance ratio (PR)
- PVUSA rating

3.1.1. Final yield(Y_F)

The total energy generated by the PV system for a defined period (day, month or year) (E) divided by the rated output power ($P_{\text{PV, Rated}}$) of the installed PV system is called the Final yield (Y_F). The rated power is provided under standard test conditions (STC) which is referred as 1000 W/m^2 irradiance, 25 °C ambient temperature and air mass 1.5 g.

$$Y_F = E/P_{\text{PV,Rated}} \tag{5}$$

3.1.2. Reference yield(Y_R)

Reference yield is the ratio of total in plane solar insolation (H_t) (kW h/m^2) to the reference irradiance (G) (1 kW/m^2). This parameter represents equal number of hours at the reference irradiance and is given as

$$Y_R = H_t/G \tag{6}$$

3.1.3. Performance ratio (PR)

Performance ratio is the ratio of the final yield (Y_F) to the reference yield (Y_R). This normalizes performance parameter with respect to the incident solar radiation and is a dimensionless quantity. It provides important information about the overall effect of losses. This parameter is used to evaluate the long term changes in the performance. The decreasing year wise PR values are indicative of loss in the performance.

$$\text{PR} = Y_F\ /Y_R \tag{7}$$

3.1.4. PVUSA rating

The PVUSA rating method is a regression method to study the PV system performance. This method uses the meteorological data of the site to calculate power at PVUSA Test Conditions (PTC), where PTC are defined as 1000 W/m^2 plane-of-array irradiance, 20 °C ambient temperature, and 1 m/s wind speed. According to the PVUSA regression analysis, power is considered to be a function of irradiance, temperature and wind speed given as

$$P = E(A + B \times E + C \times T_a + D \times W_S) \tag{8}$$

where P=AC power in kW at the specific test condition, E=plane of array irradiance (W/m^2), T_a=ambient temperature (°C), W_S=wind speed (m/s), A–D=regression constants derived from operational data.

In addition to the parameters described above, other parameters can also be evaluated for the PV systems such as the following.

3.1.5. Capacity factor (CF)

The capacity factor (CF) is defined as the ratio of the actual annual energy output ($E_{AC,a}$) of the PV system to the amount of energy the PV system would generate if it operates at full rated power ($P_{\text{PV, rated}}$) for 24 h per day for year and is given as:

$$CF = E_{AC,a}\ /P_{\text{PV,rated}} \times 8760 \tag{9}$$

3.1.6. System efficiency

Monthly system efficiency ($\eta_{sys,\ m}$) is defined as the ratio of the energy generated ($E_{AC,\ D}$) to the incident irradiance (H_t) at the module area (A_a) given as

$$\eta_{sys,m} = E_{AC,D}/H_t \times A_a \tag{10}$$

These performance parameters provide the overall system performance with respect to the energy production, solar resource, and overall effect of system losses [25]. A number of studies have been carried out on the performance evaluation of PV systems installed world-wide on the basis of these parameters. The results of some of the relevant papers on PV system performance are summarized as follows:

- Ayompe et al. [26] evaluated the performance of a 1.72 kW rooftop grid connected PV system in at Dublin, Ireland. The PV system consists of eight mono-crystalline silicon modules, each of 215 Wp rating and 17.2% efficiency. The system was monitored between November 2008 and October 2009 and its performance parameters are evaluated on monthly, seasonal and annual basis. A comparison of evaluated performance parameters of this study is made with those obtained for other locations in different countries. The annual average daily final yield (2.4 kW h/kWp-d) for the installed PV system at Dublin is found to be higher than those reported in Germany, Poland and Ballymena Northern Ireland.
- Emmanuel et al. [27] carried out the performance analysis of a 171.36 kWp grid connected photovoltaic system on the island of Crete, Greece in 2002. The system is monitored for 1 year

and the performance ratio and the various power losses (temperature, soiling, internal, network, power electronics, grid availability and interconnection) are calculated. The final yield (Y_F) ranged from 1.96 to 5.07 h/d, and the performance ratio (PR) ranged from 58 to 73%, giving an annual PR of 67.36%.

- The performance evaluation of a 1 kWp PV system consisting of 20 BP Solar double-junction thin-film amorphous silicon PV modules installed on the rooftop of a school in Warsaw, Poland in the year 2000 was carried out by Pietruszko et al. [28,29] in the year 2001 and again after 8 years of operation in 2008.The system was evaluated as per IEC 61724 standard guidelines. During the first year, the system has generated 830 kW h of electric units more than the estimated power as estimated by computer simulation. The performance ratio of the system ranged from 0.6 to 0.8 during first year of operation. Due to effect of stabilization of electrical parameters of amorphous silicon modules, in first 3 years of system operation, the PR values are found to be decreasing and are in the range from 0.52 to 0.6. The effect of meteorological parameters like, irradiance both horizontal, tilt and temperature on the system parameters such as DC and AC power output and DC voltage, is also analysed.
- Soa et al. [30] presented results of performance and comparison of four 3 kW grid-connected PV systems installed on the rooftop of a Test Centre in South Korea. Each PV array of four PV systems consisted of two multi-crystalline and two mono-crystalline PV modules. The performance was evaluated for a period of 1 year (November 2002 to October 2003). Each PV system is modelled using PVSYST software and simulated performance is compared with the measured performance. The results indicate that PR ranged from 76.8 to 78.1% for PV Systems (3 and 4) and both the system operated well without any troubles. Performance of PV system (system2) declined due to increased array losses, about 14%, because of PV module deterioration and mismatch of PV sub arrays. Simulated performance of PV systems indicated that the performance of the PV systems can be improved by 13% or more in comparison with actually measured performance identified by Field test.
- Sharma and Chandel [31] analysed the performance of 190 kWp grid interactive power plant installed in India. The performance parameters are evaluated for a period of 1 year (Jan. 2011 to Dec. 2011). The final yield, reference yield and performance ratio, are found to vary from 1.45 to 2.84 kW h/kWp-d, 2.29 to 3.53 kW h/kWp-d and 55 to 83%, respectively. The annual average performance ratio is found to be 74% after 9 years of continuous operation. The need of optimization of the tilt angle of the PV module for maximizing the power generation is also emphasized in the study.
- Makrides et al. [32] evaluated the performance of thirteen different PV technologies at three locations Cyprus, Nicosia and Stuttgart in Germany. Thirteen grid connected systems with nominal power 1 kWp are installed at these locations. The main objective of the study was to find the potential of the upcoming PV technologies for power generation through the performance assessment. The energy yield of PV systems at Cyprus is found to vary from 1600 to 1700 kW h/kWp, whereas in Stuttgart and Nicosia average annual yield is found to be 1194 and 1580 kW h/kWp, respectively. Higher yields PV systems installed at Cyprus are because PV modules are subjected to higher annual irradiance 1997 kW h/m^2 in comparison to Stuttgart 1460 kW h/m^2. Cyprus is also having hot climate and PV module temperature reaches up to 60 °C in summer. PV technologies having lower value of maximum power (P_{MPP}, %/K) temperature coefficient are found to produce highest energy yields indicating the importance of temperature loss in hot climates.
- Adhikari et al. [33] evaluated the performance of a 2.88 kWp household grid-connected PV system installed on the roof of a house at Bangkok. The installed PV system consists of 45 PV modules, connected in 4 arrays out of which 3 arrays consist of 11 modules connected in series and the last array contained 12 modules covering total area of 45.2 m^2. The data are measured for 1 year from June 1998 to May 1999 and is used to estimate the PV array output, inverter output, inverter efficiency, system efficiency, yields (reference yield, array yield, final yield) performance ratio (PR) and the losses. The annual final yield and the average performance ratio are found to be 1166 and 0.73 kW h/kWp, respectively. The monthly highest final yield is 129 kW h/kWp during June. The inverter efficiency is found to be greater than 80% throughout the study period and the maximum system efficiency is 5.4%. The result of the study indicates that the system installed in Bangkok worked satisfactorily.
- Ruther et al. [34] evaluated the performance of a double-junction a-Si BIPV grid-connected system in Brazil. The PV system consists of a 2 kWp double junction a-Si array and a DC to AC inverter. Results of performance evaluation after continuous operation of 5 years showed that PV array operated satisfactorily at a high performance ratio of 82% AC and 92% DC, averaged over the 60 months period. The influence of temperature on performance of the a-Si technology is also analysed and found that after the process of stabilization of amorphous PV panels the performance is independent of operating temperature, thus suggested that such PV technologies perform batter in warm climates.

The results of performance studies worldwide are summarized in Table 2.

The main conclusion of the performance evaluation studies are as follows:

I. The evaluation of performance parameters provides a common ground for the comparison of PV systems which differ with respect to size, technology or geographic location and helps to identify the best performing PV Technology for particular climatic conditions. The PR value is dimensionless quantity and indicates the overall effect of losses and may be used to evaluate changes in performance over a prolonged period.

II. Decreased performance ratio (PR) value and PVUSA rating during the outdoor operation are the initial signs of aging which results in loss in performance. It has been observed that the long term performance of the PV system does not remain same in the field and experiences a continuous reduction due to aging [35,36]. Performance of the PV system consequently depends upon the performance of the PV module which is the most reliable and expensive component of the PV system. Performance analysis of the PV modules under real operating conditions have shown that even the qualified module have failed or degraded [37].Thus, failure modes and the degradation mechanisms responsible for the loss in performance of PV system in the field, are needed to be identified. Identifying degradation mechanism and evaluating degradation rates have become increasingly important because photovoltaic systems are being marketed for grid linked solar power plants and stand alone residential use and for building integrated photovoltaic (BIPV) applications. Thus, in order to reduce the degradation or failures, and to improve the performance, extensive research is needed on the outdoor performance of the PV modules.

In the next section the PV module degradation studied under field conditions carried out by various researchers are discussed.

Table 2
Summary result of performance evaluation studies.

Location	PV System capacity/type	Technology type	Monitoring duration	Performance evaluation results	Comments	Reference
Dublin, Ireland	1.72 kWp/grid connected	Mono crystalline Silicon (m-c-Si)	1 Year	Annual PR and Y_F values are 81.5% and 2.4 h/d	System monitored from Nov 2008 to Oct 2009	[26]
Island of Crete, Greece	171.36 kWp/ grid connected	Poly crystalline silicon (p-c-Si)	1 Year	Y_F of the system ranged from 1.96 to 5.07 h/d with annual average PR 67.36%	System installed in 2002; performance evaluation carried out after 5 years of operation in 2007	[27]
Warsaw-Wawer, Poland	1 kWp/grid connected	Double junction amorphous thin film silicon (a-Si)	1 Year and after 8 years	PR value of the system ranges from 80% to 60% during 1st year and 52% to 60% after 8 years. Plant has generated 830 kW h during 1st year and 4430 kW h after 8 years of operation and	System installed in Dec. 2000; performance evaluation carried out after 8 years of operation	[28,29]
FDTC, South Korea	Four 3 kWp/grid connected	m-c-Si p-c-Si	1 Year	Performance results of PV systems indicate to improve 13% or more in comparison with actually measured performance identified by Field test	Systems installed in Oct 2002 and evaluated performance from Nov 2002 to Oct 2003	[30]
India	190 kWp/grid connected	p-c-Si	1 Year	Annual average performance ratio is found to be 74% after nine years of continuous operation. The need for optimization of PV module tilt angle for maximizing the power generation is emphasized	System installed in March 2003 performance evaluated from Jan 2011 to Dec 2011	[31]
Germany	1 kWp/rid connected	m-c-Si p-c-Si a-Si, HIT CdTe, CIS	1 Year	Energy yield at Cyprus is found to vary from 1600 to 1700 kW h/kWp, whereas in Stuttgart and Nicosia average annual yield is found to be 1194 kW h/kWp and 1580 kW h/kWp respectively	Performance evaluated from June 2006 to2007 of 13 different PV technologies at three locations Nicosia, Cyprus and Stuttgart in Germany	[32]
Bangkok, Thailand	2.88 kWp/grid connected	a-Si	1 Year	Annual PR and Y_F values are 73% and 3.2 h/d	System Installed in 1988; performance evaluated during first year of operation	[33]
Brazil	2 kWp /grid connected	Double junction a-Si	5 Years	PR of the system averaged over the 60 month is 82% which is very high	System shows high value of PR which is due to stabilization of thin film technology	[34]

4. PV module degradation under field conditions

The issues related to long term performance of the PV system and cost effectiveness of PV technology can only be resolved if PV modules operate reliably for 25 to 30 years in the fields [38]. Accelerated-aging tests developed for quality standards have helped a lot to improve reliability and durability of PV modules in the recent years. However, it is not possible for the accelerated tests alone to replicate the various possible degradation modes and mechanisms in the PV modules during qualification testing. Studies have shown that there are several modes of the degradation as well as reliability issues which can be determined only by testing modules in real operating conditions. The main purpose of testing of the module in the fields is to find out the dominant degradation mechanisms which restrict module performance under real operating conditions. The outcome of field testing studies then can be used to improve stability of modules in the field and review or revise the accelerated aging tests depending upon the dominant field degradation mechanisms. In the following sub-sections, construction, rating, various modes of degradation of PV modules and accelerated aging tests designed to simulate these degradation modes under controlled laboratory environment for qualification testing are discussed. A review of field degradation studies carried out by researchers is also presented to understand the dependence of accelerated aging tests on the outdoor degradation mechanism.

4.1. PV module degradation modes

Identification of degradation or failure modes of PV module and their reliability in the field was an important topic of research since 1970s when these issues were first addressed under the Flat-Plate Solar Array project sponsored by U.S department of energy [39,40]. However, till today there is lack of comprehensive knowledge about degradation and the effect of degradation on performance of PV modules even with continuous growth in manufacturing practices. Factors affecting the long term stability of PV module during field testing e.g. delamination, bubbling at solder spots, degradation of solder-joint, generation of hot spots, browning of encapsulant and cell degradation etc. have been reported recently by authors [41–43]. Study carried out by Quintana et al. [44] on the degradation modes observed in field aged module, suggested that the various modes of degradation which are finally responsible for performance loss and failure can be of five types:

- degradation of packaging materials
- loss of adhesion
- degradation of cell/module interconnects
- degradation caused by moisture intrusion
- degradation of the semiconductor device

In order to improve the module design or reduce these degradation modes, a thorough understanding of origin of these defects and their development resulting into failure is needed first. Various modes of degradation are briefly discussed as follows:

4.1.1. Packaging material degradation

Loss in the performance of module due to the degradation of packaging materials during operation in the fields is known as packaging material degradation e.g. breaking of glass, failure of bypass diode, browning of encapsulant, cracking of back sheet and delamination. Modules which carry such defects are more prone to faults like grounding and/or large module leakage current. Further, Packaging damage can also generate safety issues in the systems with high voltage because the modules which carry these defects

are not able to provide necessary insulation to prevent from electric shock.

4.1.2. Loss of adhesion

Solar cells in a PV module are covered with the encapsulant to provide protection from the operating environment. Ethylene vinyl acetate (EVA) is commonly used for this purpose and also acts as adhesive between the front glass and back sheet. Breaking of the bonds between glass/encapsulant and encapsulant/back sheet are examples of loss of adhesion and also referred as delamination. Due to delamination the incident sunlight is not able to reach the solar cells resulting in performance degradation. Addition ally, these defects stop uniform dissipation of heat resulting into higher operating cell temperatures which further degrades the performance.

4.1.3. Interconnect degradation

Changes into the structure or geometry of the solder-joints due to the segregation of metals (SbPb) in the soldering alloy results into interconnect degradation. Such structural changes in the soldering material occur due to thermo-mechanical fatigue resulting into an increased series resistance and reduced performance. In addition to increased series resistance, excessive heating of PV module, hot spot generation, arcing of solder-joint and burning of back sheet are examples of interconnect degradation. Degradation in the performance of field aged PV modules due to interconnect degradation have been reported in the past but recently no such problems are faced.

4.1.4. Moisture intrusion

Moisture can penetrate in a PV module from the laminated edges or from the backsheet and result in corrosion and increased leakage current. Corrosion result in the failure of contact between the grid lines and cell, causing loss in electrical performance. Presence of moisture in module can also increase the leakage current by reducing the electrical resistance material and resulting in degradation of performance. It can also drop the adhesional strength of bond between various component layers of the module.

4.1.5. Semiconductor device degradation

High temperature and electric field experienced by the solar cells in a PV module result into transport of atom and ion due to which lattice defects are continuously introduced. Generation of lattice defects the structure of the solar cell also changes affecting the electrical properties of the cell. Thus degradation of the solar cell also contributes to performance loss in field-aged modules. Such degradation results in an increased series resistance or decreased shunt resistance and antireflection coating deterioration. These cell specific degradation modes are important factors in analyzing PV cell and module degradation and failures. These modes gradually degrade module performance over extended operational periods.

Degradation of PV modules during the operation under actual conditions is due to individual or a combination of environmental stresses such as temperature, relative humidity, moisture, thermal cycling, UV light exposure, high voltage etc. which are experienced by it during its lifetime. It is important to identify the stresses causing degradation. The effect of stresses causing PV module degradation is determined by accelerated aging tests under laboratory conditions. McMahon [45] has reviewed various degradation modes especially related to packaging resulting in failure of thin film PV modules and discussed the role of various environmental stresses, causing failure. A summary of the degradation mechanism and corresponding stress factors causing the degradation and accelerated aging tests to study these defects is given in Table 3 [45,46].

Finally, standardized PV module qualification tests based upon the accelerated aging tests are developed to ensure the module quality and customer requirements for stability and longer lifetime. The qualification tests have strict pass/fail criteria. As module designs are continuing to change and develop there is a continued challenge to change testing procedures. Developing adequate qualification tests that may reproduce identified failure mechanisms in PV module is a continuous topic of research which involves real outdoor testing to discover the mechanisms, and indoor accelerated testing to simulate them. In the following subsection, the qualification standards presently followed by the PV industry are described.

4.2. Qualification standards

Qualification tests are accelerated stress tests developed out of a reliability testing program. Reliability is defined as the probability that an item will perform a required function. The main aim of qualification testing is to detect the presence of identified failure or degradation modes quickly in the intended environment(s). Presently, the reliability of PV modules is assessed through qualification testing as per IEC 61215 (revised) and 61646 standards [4,5]. According to qualification standard tests, eight modules are picked up randomly from the same batch and subjected to 18 rigorous tests in a fixed sequence. The modules of the whole batch out of which these modules are picked up will be regarded as qualified if performance degradation during any of these tests or after any sequence of tests is within the acceptable limits ($<5\%$). Out of the randomly selected eight modules, one module is kept as reference and is not subjected to any accelerated stress test. The second module is subjected to electrical characterization under sun simulator to determine performance at different radiation conditions, then bypass diode thermal test, and finally to hot spot endurance test to determine the ability of PV module to bear the localized heat due to partial shadowing of the cells/cracked/mismatched cells. The remaining six modules are divided into three groups with two modules in each group and subjected to different following mechanical and environmental tests as per IEC 61215 and 61646 standards:

- A set of two modules is subjected to 200 thermal cycles from -40 to $+85\ ^{\circ}C$.
- Another set of two modules undergo damp heat exposure at $85\ ^{\circ}C$ and 85% relative humidity for 1000 h, wet leakage current test and mechanical tests.
- Remaining set of two modules, is subjected to UV preconditioning (15 kW h/m^2) at 50 thermal cycles from -40 to $+85\ ^{\circ}C$, and 10 humidity freeze cycles from $+85\ ^{\circ}C$, 85% RH to $-40\ ^{\circ}C$.

The modules subjected to the tests described above, are evaluated after different stages of tests to keep a check on generation of defects which can result in module failure. These tests are:

- Visible inspection to detect defects such as cracked cells, bubbles, delamination or loss of mechanical integrity by illuminating the module area by 1000 lux.
- Open-circuit or ground faults are monitored both during and at the end of the different tests.
- The maximum power is determined to check that it is not degraded more than the prescribed limit (5%) after each test/after each test sequence.
- Insulation test to check that module has a sufficient electrical insulation regarding safety from shock. A 1000 V plus twice the

Table 3
Degradation mechanism, corresponding stress factors and accelerated aging tests.

Degradation mechanism	Stress factor					Accelerated stress test
	High temperature	Moisture	Thermal cycling	UV	High voltage	
Broken interconnect	✓	✓			✓	Thermal cycle
Broken cell	✓				✓	
Solder bond failures	✓	✓	✓		✓	
Junction box failure	✓	✓				
Open circuits leading to Arcing	✓				✓	
Corrosion	✓	✓			✓	Damp heat exposure
Delamination of encapsulant	✓	✓	✓	✓	✓	
Encapsulant loss of adhesion and elasticity	✓	✓	✓		✓	Humidity freeze
Encapsulant discoloration	✓			✓		UV test
Hot spots	✓					Hot spot test
Shunts at the scribe lines	✓	✓				
Electrochemical corrosion of TCO	✓	✓			✓	Dry and wet insulation resistance
Ground fault		✓			✓	
Bypass diode failures	✓		✓			bypass diode thermal test

maximum voltage is applied to the modules for the insulation test and resistance should not be less than 40 MΩ/m^2 of module area.

- In wet leakage current test the output terminals of the module are shorted and a voltage equal to twice the module maximum power voltage is applied between shorted terminals and water bath for 2 min. The insulation test and resistance should not be less than 40 MΩ/m^2 of module area. Wet leakage current test is performed after the end of each sequence and after the damp heat test.

If all the eight modules pass the tests to which they are subjected then it is concluded that the batch of module meets the qualification standard. If two or more modules are not able to pass the tests, the module type does not meet the qualification standard. If a single module fails any test, then two new modules of the same batch are subjected to same tests which have resulted in failure and if both modules pass the repetition of the test only then module are certified as Qualified. Once qualified, these modules are guaranteed to operate in the field with at least 90% of its initial nominal power after 10–12 years and 80% after 20–25 years of operation.

The Qualification Tests IEC 61215 for crystalline PV modules and IEC 61646 for thin film PV modules, are important and valuable. PV modules that have passes the qualification tests are expected to survive in the field and do not have design flaws which leads to infant mortality, but these have limitations too. Chianese et al. [47] studied the long term degradation of crystalline PV modules under real outdoor conditions for 21 years at a 10 kWp LEEE TISO plant. Realini [48] in mean time before failure (MTBF) project studied the behavior of the same 21 year exposed 10 kWp PV plant. Detachment of back sheet tedlar has been observed in the modules whereas damp heat and thermal cycling qualification tests result in generation of defects such as EVA delamination which are quite different. Thus it is quite difficult to equate these stresses with those experienced by a module operating in the field as part of a PV system on a quantitative basis. Just passing the qualification tests does not tell that how longer the module will survive in the fields. As the PV industry is growing rapidly, there is a need for qualification standards to be more quantitative. The PV modules are generally warranted for 25 years in the field by the manufacturers but there is no standard qualification test which can estimate the module life time. In order to be more quantitative the combination and level of stresses to be accelerated is needed to be determined to represent the 25 years of lifetime. Further, the stress levels are also site dependent where the PV modules are deployed as well as mounting. As the PV industry had started finding applications in all climate zones and in a variety of use configurations (open rack, direct-roof mount, BIPV etc.), there is a need of qualification standards that can differentiate PV modules according to their durability for specific use. "Durability of a PV module is defined as its ability of withstand under the environmental stress". In order to address all these issues International PV module quality assurance forum is organized and PV quality assurance task force is formed [49]. Presently efforts are underway towards creating a comparative rating system for the various conditions encountered by PV modules in the field. A comparative rating system will serve the following purposes:

- will be a tool for PV manufacturers to design more durable modules and validate their designs for a range of applications
- will provide information for customers to compare products and select those that best meet their needs
- will provide insurance companies a basis for determining rates in different climate zones.

4.3. Accelerated aging tests

In accelerated aging test, stress is applied to a test PV module until failure whereas in qualification testing, stresses are applied only for a prescribed and limited duration. The stress factors that can be accelerated are: total irradiance, UV irradiance, temperature, humidity, or combinations of these factors. The accelerated testing must address the observed field failure modes and must cause degradation of the product as seen in the field. As the qualification tests are accelerated stress tests designed to address the identified field failure modes, these can be used for extended time to develop the reliability tests. Using this approach Wohlgemuth and Kurtz [50] proposed a method for assessing the long-term reliability and durability of new lower-cost PV modules using accelerated testing. Effort is now underway to establish a methodology for making the accelerated stress tests more quantitative [51]. The long-term goal is to develop a quality rating system that provides comparative information about the relative durability of the PV modules when exposed to the variety of stresses. This will help to predict the module lifetime with more accuracy

4.4. Module lifetime

PV module lifetime is defined as the duration of time after which module cannot be used because of issues like safety, a catastrophic event, or when the output power has degraded below

a minimum acceptable value. From the manufacturer point of view, the lifetime is the number of years for which the module is guaranteed with an output power above a certain value for example 80% of the initial value. Continuous performance measurements during the long term exposure have shown that degradation of output power in PV modules and systems varies linearly with time and helps in determining the degradation rate [52]. The lifetime can be estimated by using degradation rate, if the degradation limit is known using following relation:

$$t_L = \frac{100\% - L_D}{R_D} \tag{11}$$

where t_L is the lifetime in years, R_D the degradation rate in percent per year and L_D is the degradation limit in percent. Va´zquez and Rey-Stolle [53] developed a photovoltaic reliability model based upon the field degradation studies and discussed the issues related to lifetime and warranty. The author′s recommended that the yearly degradation rate must be less than 0.5% in order to provide 25 years warranty. Lifetime of a module can be predicted by a relatively short set of accelerated stress tests. However, a technical basis for predicting lifetimes has not been established. Krutz et al. [54] proposed comparative standards in an effort to estimate the expected lifetimes as a function of the operational conditions to find the range of stresses that is to be applied. These standards may not be perfect, but can be considered as an important approach in this context.

4.5. Field degradation studies of PV modules to correlate between accelerated aging tests and field tests

A number of long term field testing studies of crystalline Si (c-Si) and thin film PV modules, have been carried out to understand PV module degradation mechanisms. However, studies correlating the PV module field degradation with accelerated aging tests in the literature are scarce. In this section, significant information on such studies, is presented. Degradation of PV modules can be divided in to two categories one related to degradation of solar cell and other to packaging like encapsulant browning, delamination and interconnects issues. Saitoh et al. [55] reviewed light induced degradation in c-Si solar cell. The reported light induced degradation, is one of the few changes that can be related to the solar cell degradation and referred as Staebler–Wronski effect. The performance of the solar cell of module degrades during initial light exposure for few hours and stabilizes at levels 1–5% loss in the short-circuit current. In order to reduce the light induced degradation methods using various doping techniques are also discussed. Lund et al. [56] reviewed field and laboratory studies carried out on the performance of photovoltaic modules manufactured using different techniques for their long term stability. In an effort to correlate between field and laboratory conditions, authors tested a-Si:H modules in the field and in the laboratory, comparison of the effect of light induced degradation on the performance of PV module indicate that a-Si:H modules suffer maximum degradation when exposed to light in open circuited condition and minimum when operated at a load close to maximum power point.

There are number of mechanisms of degradation related to packaging some of the important ones corrosion and electromigration in the contact layers and at inter-connects. The contact degradation results in increase in series resistance whereas interconnect degradation can affect both series and shunt resistance. Degradation due to corrosion can introduce a voltage between an anode and a cathode leading to leakage current and result in the form of chemical changes in the cell/contact material. Cueto and McMahon [57] study the effect of high voltage biasing on PV modules reliability at National Renewable Energy Laboratory (NREL). Two crystalline and two amorphous silicon PV modules are subjected to the high voltage stress of ($\pm$600 V) in the fields for 3 years. Leakage current through the soda lime silicate glass was found to be the dominant degradation mechanism which can result into failure due corrosion of PV cell metal contacts.

Meyer and van Dyk [58] at NREL developed degradation assessment methodology of a completely encapsulated PV module, which allows the determination of various module parameters such as short-circuit current, open-circuit voltage, maximum power, fill factor, series resistance, shunt resistance, saturation current, ideality factor, the cell where the worst-case hot-spot condition will occur, and temperature coefficients. These parameters were then monitored at regular intervals to evaluate degradation. In a follow up study by same authors, employed the methodology developed in [59] to study degradation in the performance in the three thin film technology module exposed in outdoors for 130 kW h/m^2 [60]. The result indicate that single junction amorphous (a-Si:H) thin film modules suffered 50% reduction in efficiency, efficiencies of a-Si:H/a-SiGe:H module degrade by 13% and the $CuInSe_2$ module by 10%. The results indicate the formation of hot spots in the $CuInSe_2$cells because of localized heating, which has reduced module shunt resistance. Samples from two $CuInSe_2$ thin film modules degraded due to formation of hot spots and shunt paths during periodic indoor and outdoor measurement are studied with scanning electron microscope and energy dispersive X-ray spectrometer for further microanalysis [60]. Studies employing such sophisticated instruments for degradation analysis are very less reported because there is no standard methodology of obtaining samples from the laminated modules to carry out such studies. Recently, progress has been made in this area. King et al. [61] describe both destructive and non-destructive procedures applied to degradation analysis of field-aged modules.

Most commonly used encapsulant material in photovoltaic application is EVA, its discoloration and stability have received significant attention for improving the performance and durability of the PV modules. In order to quantify the adhesive strength of EVA, a destructive procedure of obtaining samples from field aged c-Si modules is developed at Florida Solar Energy Center [62]. The adhesive shear strength is measured by measuring the peak torque while extracting the sample. The results of the study indicated that adhesional shear strength is weaker at EVA/cell interface than Glass/ EVA interface and after 7 years of outdoor exposure, the shear strength is only 20% of unexposed module samples several researchers have reported the degradation in performance due to EVA browning because of ultraviolet exposure and oxidation resulting in loss in the transparency and photon availability [63–65].

Water penetration through the laminated edges and back sheet of PV module is another driving force for many degradation mechanisms. Mon et al. [66] at Jet Propulsion Laboratory, USA, studied water module interaction and suggested that thin-film PV modules are more prone to water penetration than c-Si or mc-Si modules because the thin-film active material is located at the encapsulant/substrate interface, whereas c-Si and mc-Si are surrounded by the encapsulant on all sides. Recent studies about the moisture intrusion in PV modules deployed in the field′s shows that moisture penetration results into delamination and reduces the active area of the module [67,68].

Carlsson and Brinkman [69] in an effort to correlate between field test and accelerated aging test studied the performance degradation of CdTe PV module with Sb back contacts, deployed the PV modules in outdoor conditions which showed significant degradation in the performance during the exposure of one and half year. In order to identify the degradation mechanism small area samples are made from the field aged modules and the

current–voltage and capacitance–voltage and resistance measurements are carried out. The results indicate that one of the root causes of degradation is the decrease in the doping concentration near the CdTe/Cds junction and increase in the resistance. It is also suggested that the bias voltage might be the driving force for the progression of the degradation. Degradation studies described above are summarized in Table 4.

Most studies on degradation discussed above have been carried out on failed field-aged modules. Studies reported on healthy field-aged modules which can provide the data of satisfactory performance of PV technology in the field through evaluation of the degradation rate are very less. Thus, in order to define degradation rates authors around the world has recently started studying performance of different technology modules together at different climatic conditions.

Carr et al. [37] at the Australian Cooperative Research Center Perth, Australia evaluated the performance of five different technology PV modules from seven different manufacturers for 16 months of outdoor operation. The results of the study indicate that mono and polycrystalline silicon PV modules show 2% per year power reduction where as amorphous and CIS solar modules exhibited a significantly higher power reduction.

Raghuraman et al. [70] evaluated performance of 44 modules from eight different manufacturers and three different technologies in Mesa, Arizona under hot-arid climatic conditions for 2.4 to 6.7 years. Mono-crystalline and polycrystalline silicon modules exhibited low power degradation (approx 0.5% per yearly) while a-Si multi-junction modules degraded more (1.16% per yearly).

Marion and Adelstein [71] at Solar Energy Research facility (SERC) reported the performance of two PV systems installed on the roof top of SERF building from 1994 to 2002. Each of the PV system consists of 140 PV modules. PVUSA method is used to quantify the degradation rate and results indicate that performance of both PV systems is reducing at a rate 1% per year. The reduction in the performance is regarded as an effect of aging.

A study on power degradation of crystalline silicon PV modules is presented jointly by the Japan Quality Assurance Organization and Solar Techno-Center [72]. Modules are operated outdoors for 10 years in Hamamatsu (Japan) and average power reduction found to be 6.2%, however about but 10% of the PV modules have suffered reduction in power more than 10%.

Another interesting work is carried out by Dunlop and Halton [73] at Institute for Environment and Sustainability, Italy, studying the performance of 40 silicon (poly and mono) crystalline PV modules with different encapsulation and from six different manufacturers operating for 20–22 years in the fields. Modules encapsulated with silicon sealant showed 6.4% average power degradation while modules encapsulated with EVA and a Tedlar aluminium back sheet exhibited 14.8% mean power degradation.

Realini et al. [74] in the mean time before failure (MTBF) Project analysed the performance of a 10 kW PV system installed at Lugano, Switzerland after 21 years of operation. PV system consists of crystalline silicon PV modules and after 21 years a 0.5% per year power degradation is reported.

Sastry et al. [6] studied the performance degradation of mono crystalline PV modules supplied by eleven manufacturers, at the Solar Energy Centre, under Indian climatic conditions, for a period of 10 years. The modules from eleven manufactures are divided into five groups for the sake of convenience in analyzing the data. The degradation in the output power of modules form the manufacturer whose module qualified under IEC 61215 standards found to range from 5 to 16.5% after 10 years. The degradation in the output power of modules form the manufacturer whose module are not qualified under IEC 61215 standards found to range from 17 to 33% after 10 years. In this study it was found that even the well qualified modules have failed or degraded more than the expected levels and suggested that there is a need to review the PV qualification standards especially for Indian climatic conditions, if the modules are to perform for more than 20 years in the field.

Jordan and Kurtz [75] recently reviewed the degradation rates from the field testing studies carried out during the last 40 years and concluded that the degradation rates observed in the PV modules/systems deployed before and after year 2000 have significantly reduced which indicates the substantial improvement in the stability of the PV modules or systems.

In conclusion, bridging the gap between accelerated aging tests and field tests still require more in depth studies. Based on correlation between accelerated aging tests and field tests, ultimately the aim is to predict the field lifetime of a module from the results of the accelerated aging test. A better understanding of the mechanisms that start module degradation resulting in failure, is needed. Once this information is understood, it can be used to develop models to properly quantify the system performance, reliability, and cost. In the following section, the failure mode analysis techniques to understand degradation mechanism are discussed.

Table 4
Summary of degradation studies.

Reference	Type of PV technology under study	Identified degradation mechanism	Comments
Lund et al. [56]	Amorphous Si (a-Si:H)	Light induced degradation	a-Si:H Modules are tested in the field and in the laboratory
Cueto and McMahon [57]	Crystalline Si Amorphous Si	Leakage current through the soda lime silicate glass	PV modules are subjected to the high voltage stress of (±600 V) in the fields for 3 years
Meyer and van Dyk [59]	Amorphous (a-Si:H) Amorphous (a-Si:H/a-SiGe:H) $CuInSe_2$	Formation of hot spots in the $CuInSe_2$ cells because of localized heating	Samples from the degraded module are studied using SEM and energy dispersive X-ray
Mon et al. [66]	Crystalline Si (mono and poly) Amorphous Si (a-Si)	Moisture ingress	Thin-film PV modules are found to be more prone to water penetration than c-Si or mc-Si modules
Carlsson and Brinkman [69]	Cadmium telluride (CdTe)	Decrease in the doping concentration near the CdTe/Cds junction and increase in the resistance	Small area samples are made from the field aged modules and the current–voltage and capacitance–voltage and resistance measurements are carried out

5. Failure mode analysis and most promising techniques

Recently efforts are made to understand the degradation modes and failure of the field aged modules which resulted in the development of new techniques to identify the degradation mechanism. These techniques have helped in optimizing the manufacturing process and improving module lifetime. However, not much work has been reported on the degradation or the failure mode analysis of the field aged modules due to lack of established techniques for identifying the degradation mechanism (destructive or non destructive) and standard techniques of dissecting encapsulated module for sample extraction. In the failure mode analysis the initial step is, to identify the physical location of the degraded/failure site. The inspection techniques used, are as follows:

- Electrical characterization
- Visual inspection
- Ultrasonic inspection
- Infra red imaging (IR imaging)
- Electroluminescence imaging (EL imaging)

Once the degraded/failure site is located, the microscopic analysis can be performed for detailed understanding of the degradation and causes responsible for it. The analytical techniques have been found very useful for microscopic analysis of the degradation/failure as these techniques are capable of identifying the defects as well as the progression of defects which result in failure [76]. There are several analytical techniques used in microanalysis, however, the most significant and the recently reported techniques are:

- Attenuated total reflectance infrared microscopy (ATIR)
- Scanning electron microscopy (SEM)
- X-ray micro-tomography

The first indication that the module has degraded/failed is provided by the reduction in its output power (P_{max}) however a clear indication is presented by the complete *I–V* curve i.e. the electrical characterization of PV module [77]. The electrical characterization of field exposed modules, is performed using large area pulsed solar simulator as per the international standards [4,5]. After the confirmation of degradation, the modules are subjected to the visual inspection. During the visual inspection module is checked for the various visual defects such as encapsulant browning, delamination and bubbles formation in the encapsulant, back sheet polymer cracks, junction box connections corrosion, oxidation and discoloration in junction cables etc. under the 1000 lux light source as per standards. The next step is to locate the exact position of the defect for which several techniques have been developed and initial documentation of such techniques is done by Hund and King at Sandia National Laboratory [78] and is briefly explained as follows:

5.1. Ultrasonic inspection technique

The ultrasonic inspection of PV module basically consists of two methods, transmission method and pulse-echo method as shown in Fig. 5. In both the methods the PV module, is scanned by moving ultrasonic transducer along with the X–Y indicator assembly over the PV module. In the transmission method the PV module is scanned by passing the ultrasonic energy through it and the attenuated ultrasonic signal is recorded. This method helps to locate only X–Y location and size of the defect. In the pulse-echo method the ultrasonic pulses reflected back from the defects is recorded. This method helps to identify the debonding of cell/assembly of cells in module a part from the X–Y location of the defect. In order to show the usefulness of the ultrasonic inspection the same authors have presented the results of the ultrasonic scans of PV concentrator cell assembly during humidity freeze testing (−40 to 110 °C) and the results have indicated a significant debonding at the ceramic/aluminum interface.

5.2. Infrared/thermal imaging

Another technique most commonly used for identifying the degradation/failure site in a field exposed module is the infrared/thermal imaging. This technique utilizes the concept of localized heat generation because of joule heating effect due to the poor contacts, shunted cells, short circuits. This happens because the cells which are generating less current as compared to the other cells connected in the series become reverse biased and start behaving like resistors and dissipate heat. This dissipated heat results into a temperature gradient which during thermal imaging appear as bright spots. This technique consists of a camera sensitive to infrared radiation of 3–15 μm range. The thermal imaging can be done in two ways forward bias imaging and reverse bias imaging.

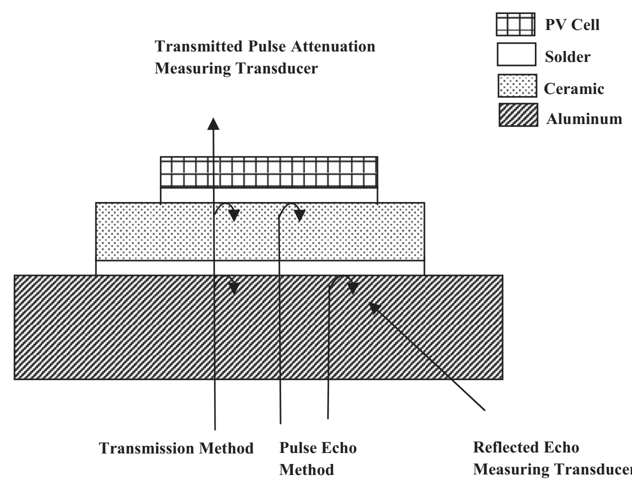

Fig. 5. Ultrasonic inspection methodology.

In the forward bias thermal/IR imaging the field exposed module is connected to a power supply with the module in a forward-biased condition. Then the current approximately two times the nameplate short-circuit current of the module is made to flow through the module with the power supply. As the module gets heated up, IR images were recorded using IR camera. Defects like increased series resistance, hot spot and weak connect are best identified by this method. During reverse bias imaging same procedure is adopted except the module connected to power supply is in reverse biased condition. This approach helps to identify the Ohmic shunts. The disadvantage of both of these methods is that the localized heat generated, is lost when a thermal equilibrium is achieved to avoid this another technique lock-in thermography is devised. Researchers involved in studying and identifying the degradation/failure in the field aged modules is using this technique frequently. In a study done by Kaplani E. to detect the effect of degradation on the field aged c Si PV modules from 18 to 22 years used the thermal imaging technique [79]. The defect site located through IR imaging and the *I–V* curve analysis showed a good agreement between the source of electrical performance degradation and the degradation effects in the defected cell identified by the IR thermography.

5.3. Electroluminesence imaging (EL imaging)

Electroluminescence imaging (EL imaging) is based upon the principle that as PV materials can efficiently convert photons into energy, similarly they can convert input energy into photons. For electroluminescence and photoluminescence the input energy can be in the form of electrons and photons respectively. Electroluminesence (EL) imaging is the most commonly used for failure analysis because the emission intensity is proportional to both carrier lifetime and current density. Poor contacts and non-uniform current can easily be detected with electroluminescence. Electroluminesence (EL) imaging is helpful in differentiating in the increased series resistance and reduced parallel resistance which is difficult because both of these defects lead to hotter areas in IR imaging. Photoluminesence (PL) imaging has recently been introduced for the failure analysis applications.

Studies involving these techniques for the failure analysis as well as quality control of PV modules have been reported recently [80,81]. Results of the studies indicate the usefulness of these techniques as during the manufacturing process of PV modules, cells are inter-connected in series through solder joints and finally it is laminated and in between this process testing of the PV module can-not be performed thus, non-destructive test methods are required for the inspection of photovoltaic (PV) modules.

Quintana et al. [82] has reported computed tomography (CT) using X-rays as another non destructive technique. Results show how advanced computed tomography (CT) can be utilized for studying the reliability and failure analysis issues such as μ-cracks in Si cells of PV module.

Ketola and Norris [83] investigated the degradation mechanism of solar PV modules during the extended damp heat exposure using the electroluminesence imaging (EL). In order to introduce the aging effect in the PV modules authors applied damp heat accelerated aging test several times larger than 1000 h as per IEC standard to PV modules with silicone and ethylene vinyl acetate (EVA) as encapsulation materials. Results of analysis of the aged PV modules by electroluminescence (EL) imaging indicate that factors other than corrosion at the electrical interconnects might have occurred. The techniques described above are found to be very effective in locating the defects which are not observable with naked eye or low power optical microscope. Once the position of the defect is located the defected area is extracted carefully without changing the physical and chemical properties for further microscopic characterization.

Extracting the defect from the module itself is challenging job because mostly a tempered glass is used as a superstrate in crystalline solar modules. There is no standard sample extraction methodology from located defected site of the module reported in the literature. Heating the module so as to soften the encapsulant and removing the defective cell has been suggested for sample extraction, however heating can itself introduce several physical and chemical changes. Another approach of sample extraction by coring the PV module from the backside is described from Sandia Lab by King et al. [61]. Method for sample preparation if the identified defect involves the tempered glass is also described by the same authors. In case if the defect does not involve the tempered glass then one can break the glass and extract the sample by cutting it from the area of interest.

An interesting work on failure analysis of PV module using analytical techniques for microanalysis is reported by Gambogi et al. [84]. Several analytical techniques applied for failure analysis of PV module applied to PV module are initially reviewed by the authors and later on analytical techniques such as ATIR, SEM and X-ray micro-tomography are applied on the PV module which has failed during the impulse voltage testing as per qualification testing standards. During the investigation an internal discharge which has occurred is found to be the root cause of failure in impulse voltage testing. Micro-tomography is used to locate the interface at which the discharge initiated. Further investigation of the discharge path is done using ESEM identified the presence of copper shards which have caused the discharge at high voltage in the defective areas. Further investigation conducted to find out from where these particles have penetrated into the laminate structure, it is suggested that this might have occurred during the EVA encapsulation process. Various failure mode analysis techniques described above are summarized in Table 5.

Detailed investigations of the degraded/failed PV modules employing the analytical techniques along with the defect site localization techniques are very promising. Using these techniques collectively has provided as extra insights to thoroughly understand as well identify the physical and chemical changes that have initiated the degradation process. The outcome of such studies will be helpful for improving the PV module design and reliability.

6. Conclusion

In this study, the most significant recent information available on the performance, degradation and reliability of the PV modules has been reviewed. The main conclusions are as follows:

- The power output of PV modules deployed under outdoor conditions does not remain same and experiences a continuous degradation due to aging. The degradation in power output varies linearly with time during the long term outdoor exposure.
- The outdoor performance and degradation studies of PV systems installed in different geographical locations and climatic zones help in identifying the stresses such as temperature, humidity, UV light exposure, moisture, thermal cycling etc. causing degradation, and to reliably correlate between the controlled laboratory conditions to harsh outdoor conditions to develop adequate qualification standards.
- The present qualification tests indicate the infant mortality of PV modules and are not sufficient to estimate the module life

Table 5
Summary of failure mode analysis techniques.

Name of the technique	Type of defect identified
(a) Non destructive	
ultrasonic imaging	Capable of locating air voids, debonding and delamination which are not visible
Infrared/thermal imaging	Hotspot generation, increase in the series resistance
Electroluminesence imaging (EL imaging)	Helpful in differentiating in the increased series resistance and reduced shunt resistance which is difficult because both of these defects lead to hotter areas in IR imaging
Computed tomography (CT) using X-rays	Studying reliability and failure analysis issues such as μ-cracks in Si cells of PV module
(b) Destructive	
scanning electron microscopy (SEM)	Study the morphology of the defect sample
X ray tomography	Studying the chemical changes which have occurred in the area of interest

time under field conditions. The PV industry has started finding applications worldwide in all the climatic zones with various configurations which makes the task more challenging. However, efforts are underway towards making qualification tests more quantitative by creating a comparative rating system for various conditions encountered by the PV module in the field worldwide.

- Newly developed methods and analytical tools described in Section 5, require to be utilised along with outdoor performance and degradation evaluation in order to completely understand the degradation/failure mechanism of PV modules due to physical and chemical changes taking places at different interfaces.

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